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Pathways to sustainable bioenergy

Navigating the energy-ecosystem services-biodiversity nexus in agricultural landscapes

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LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

Pathways to sustainable bioenergy

Navigating the energy-ecosystem services-biodiversity
nexus in agricultural landscapes

JOSEFIN WINBERG

CENTRE FOR ENVIRONMENTAL AND CLIMATE SCIENCE | LUND UNIVERSITY



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nexus in agricultural landscapes

Josefin Winberg



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DOCTORAL DISSERTATION

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Prof. Jens Dauber

Thünen Institute of Biodiversity & Technical University Braunschweig, Germany

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Abstract: Bioenergy plays a major role in the renewable energy supply and is projected to be an important part of the path towards a decarbonised society. Over the past decade, increasing attention has been given to agricultural bioenergy to act as a multifunctional climate mitigation strategy. Energy crops may mitigate climate change while simultaneously contributing to reducing the negative environmental impacts of agriculture if placed in intensive cropping regions or serve as alternative land use and source of income when placed on unused or marginal land. The deployment of extensive bioenergy production for energy is however potentially limited by competition with food, feed, and fibre production, as well as the need for nature conservation. To avoid conflicts between climate mitigation, food security, and biodiversity conservation, bioenergy strategies have to be thoroughly evaluated to ensure sustainable policy recommendations. This thesis aims to increase the knowledge of sustainable bioenergy production from Swedish agricultural landscapes and to understand the challenges and opportunities of extended agricultural bioenergy production for other societal goals. With a main focus on sustainable land use, I have studied the interaction between different bioenergy strategies, ecosystem service supply, and biodiversity conservation. I have combined methods from ecology, economy, and geography to provide a holistic view of agricultural bioenergy, covering different landscape contexts, production sites, biomass sources, spatiotemporal scales, and taxonomic groups. From the four chapters of this thesis, three main findings can be communicated: i) both ecosystem services and biodiversity impacts need to be considered when assessing bioenergy strategies to avoid trade-offs between climate mitigation and biodiversity conservation, ii) integrated production of bioenergy crops in intensive arable cropping regions may positively affect multiple ecosystem services and taxonomic groups if it is combined with protection of species-rich habitats, however, it requires substantial financial incentives and has consequences for food production, iii) there is a high risk of overestimating bioenergy potentials from marginal and unused land if land characteristics and alternative use-values are not considered. These results highlight the challenges of increasing agricultural bioenergy production without compromising other societal needs, but they also show the opportunities for sustainable bioenergy to contribute to a fossil-free society if coupled with sustainable food systems and broader reductions in energy use and consumption.

Keywords: renewable energy, climate mitigation, biodiversity conservation, multifunctionality, marginal land, abandoned land, land-use change, biomass production, afforestation, energy grass

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*“You can’t go back and change the beginning,
but you can start where you are and change the ending.”*

C.S. Lewis

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Abstract

Bioenergy plays a major role in the renewable energy supply and is projected to be an important part of the path towards a decarbonised society. Over the past decade, increasing attention has been given to agricultural bioenergy to act as a multifunctional climate mitigation strategy. Energy crops may mitigate climate change while simultaneously contributing to reducing the negative environmental impacts of agriculture if placed in intensive cropping regions or serve as alternative land use and source of income when placed on unused or marginal land. The deployment of extensive biomass production for energy is however potentially limited by competition with food, feed, and fibre production, as well as the need for nature conservation. To avoid conflicts between climate mitigation, food security, and biodiversity conservation, bioenergy strategies have to be thoroughly evaluated to ensure sustainable policy recommendations. This thesis aims to increase the knowledge of sustainable bioenergy production from Swedish agricultural landscapes and to understand the challenges and opportunities of extended agricultural bioenergy production for other societal goals. With a main focus on sustainable land use, I have studied the interaction between different bioenergy strategies, ecosystem service supply, and biodiversity conservation. I have combined methods from ecology, economy, and geography to provide a holistic view of agricultural bioenergy, covering different landscape contexts, production sites, biomass sources, spatiotemporal scales, and taxonomic groups. From the four chapters of this thesis, three main findings can be communicated: i) both ecosystem services and biodiversity impacts need to be considered when assessing bioenergy strategies to avoid trade-offs between climate mitigation and biodiversity conservation, ii) integrated production of bioenergy crops in intensive arable cropping regions may positively affect multiple ecosystem services and taxonomic groups if it is combined with protection of species-rich habitats, however, it requires substantial financial incentives and has consequences for food production, iii) there is a high risk of overestimating bioenergy potentials from marginal and unused land if land characteristics and alternative use-values are not considered. These results highlight the challenges of increasing agricultural bioenergy production without compromising other societal needs, but they also show the opportunities for sustainable bioenergy to contribute to a fossil-free society if coupled with sustainable food systems and broader reductions in energy use and consumption.

Populärvetenskaplig sammanfattning

Två av de största hoten mot mänskligheten och vår omgivning är de pågående klimatförändringarna och förlusten av biologisk mångfald. Dessa är två tätt sammankopplade kriser eftersom klimatförändringar påverkar förutsättningarna för allt liv på jorden, samtidigt som en förlust av biologisk mångfald förvärrar konsekvenserna av ett förändrat klimat. Det komplexa sambandet mellan klimatförändringar och biologisk mångfald kräver att lösningar tar hänsyn till båda kriserna, så att en klimatåtgärd inte sker på bekostnad av biologisk mångfald och vice versa. Ett centralt fokus för klimatåtgärder är utsläppsminskningar från energisektorn. Det kan ske bland annat genom effektivisering och minskad användning av energi, samt genom att fossila bränslen och utsläppsintensiva energikällor fasas ut och ersätts av förnyelsebar energi. Inom Europa och i Sverige har bioenergi varit en viktig källa till förnyelsebar energi under det senaste decenniet och förutspås spela en viktig roll även framöver för att vi ska nå de uppsatta klimatmålen. Bioenergi är energi (t.ex. bränsle, värme, elektricitet) som produceras från biologiskt material så som energigrödor, skogsbiomassa och restavfall. Dock har hållbar produktion av bioenergi flera utmaningar eftersom det konkurrerar om mark och biomassa som kunde använts till annat. Detta kan få oönskade konsekvenser för andra samhällsmål så som livsmedelsproduktion och bevarande av biologisk mångfald.

Hur vi människor nyttjar naturresurser och använder mark har en stor påverkan på arter och dess livsmiljöer, men är också en starkt bidragande faktor till klimatförändringar, bland annat på grund av utsläpp av växthusgaser och lagring av kol i mark och vegetation. För att säkra en långsiktigt hållbar bioenergiproduktion som bidrar till utsläppsminskningar och inte konkurrerar med bevarandet av arter och dess livsmiljöer behöver hänsyn tas till vilken typ av biomassa som används samt hur och var denna är producerad. I denna avhandling har jag fokuserat på bioenergiproduktion från jordbrukslandskapet med syftet att undersöka hur olika strategier för att öka produktionen av jordbruksbaserad bioenergi påverkar biologisk mångfald och ekosystemtjänster (produkter och tjänster från ekosystem som gynnar oss människor). För att skapa en helhetsöversyn av bioenergistrategier har jag studerat olika typer av biomassa, däribland livsmedelsgrödor, energigrödor och skogsplantage, som producerats på olika typer av mark i jordbrukslandskapet. Dessa marktyper inkluderade jordbruksmark, gräsmarker, obrukad mark och marginalmark (d.v.s. mark som är marginellt lönsam att bruka). De studerade

typerna av biomassa och produktionsplatser skiljer sig i sin markanvändningsintensitet, men är också mer eller mindre viktiga för livsmedelsproduktion. I min avhandling har jag även kombinerat flera olika metoder för att utvärdera bioenergistrategier vilket gjort att jag kunnat inkludera studiesystem på olika geografiska skalor med olika ekosystemtjänster och organismer i fokus.

Huruvida hållbar bioenergiproduktion kan ske i jordbrukslandskapet eller ej har utvärderats av forskningsstudier under flera decennier och det finns dessvärre inga enkla svar. Mina studier visar att introduktionen av en flerårig energigröda på intensivt brukad jordbruksmark bidrar till ett mer varierat jordbrukslandskap, något som ofta medför positiva effekter för flertalet ekosystemtjänster och artgrupper. Inverkan på ekosystemtjänster och biologisk mångfald studeras dock sällan tillsammans, vilket gör att vi vet lite om den totala miljöpåverkan av sådana strategier. Dessutom finns det många arter som inte gynnas av en intensiv bioenergiproduktion samtidigt som en ökad bioenergiproduktionen få sekundära effekter i landskapet om en ändrad produktionsinriktning i jordbruket gör att artrika miljöer går förlorade. Även om bioenergigrödor kan förbättra miljöförhållanden inom jordbruket genom exempelvis ökad kolinlagring och minskad användning av bekämpningsmedel kan de inte ses som en bevarandeåtgärd för biologisk mångfald. Bevarande av biologisk mångfald i jordbrukslandskapet kräver istället riktade bevarandeåtgärder där arters specifika behov av livsmiljöer tillgodoses.

Bioenergiproduktion från aktiv jordbruksmark har dock fått mycket kritik inom både politik och forskning då energiproduktionen riskerar att konkurrera med matproduktion, vilket i så fall ökar risken för höjda matpriser och indirekta markanvändningsförändringar på andra platser för att kompensera för den förlorade produktionen. Uppmärksamheten har därför vänts mot mark som inte anses fylla en viktig funktion för livsmedelsproduktion, så som marginalmark eller obrukad mark. Dessa marktyper är ofta vagt definierade och deras potential för biomassaproduktion grundas till stor del på grova uppskattningar. Mina studier visar dessutom att arealen obrukad mark i södra Sverige är liten och dessa marker kan ha hög artrikedom. Marginalmark målas ofta upp som den ultimata lösningen på hur markanvändningskonflikterna från bioenergiproduktion kan minska, men min avhandling visar att konflikterna med matproduktion, bevarande av biologisk mångfald och rekreation till stor del kvarstår.

Min avhandling visar på vikten av att inkludera både ekosystemtjänster och biologisk mångfald i utvärderingar av bioenergistrategier för att undvika konflikter mellan klimatåtgärder och bevarandeåtgärder. Detta kräver att vi bättre förstår vilka livsmiljöer som gynnar biologisk mångfald för att styrmedel ska kunna utformas som säkerställer att dessa ekosystem bevaras samtidigt som klimatförändringar bekämpas. Även om hållbart producerad bioenergi kan vara en del av vägen mot ett fossilfritt samhälle krävs även andra samhällsförändrande åtgärder som minskar vår totala energianvändning och konsumtion för att de globala klimatmålen ska nås.

List of papers

Chapter I

Winberg J., Smith H. G., Ekroos J. (2023) Bioenergy crops, biodiversity and ecosystem services in temperate agricultural landscapes - A review of synergies and trade-offs. *GCB Bioenergy*, 15(10), 1204-1220.

Chapter II

Winberg J., Ekroos J., Eklundh L., Smith H. G. (2024) Constraints on the availability of marginal land for bioenergy production in southern Sweden. *Under review in Biomass and Bioenergy*.

Chapter III

Winberg J., Ekroos J., Smith H. G. (2024) Abandonment or biomass production? Phytodiversity responses to land-use changes of semi-natural grasslands in northern Europe. *Biological Conservation*, 294, 110632.

Chapter IV

Winberg J., Larsson C., Stjernman, M., Ekroos J., Clough, Y., Smith H. G. (2024) Grass leys as multifunctional climate mitigation strategy in intensive cropping systems require high financial incentives. *Manuscript*

Additional published papers not included in the thesis

Thomson Ek, H., Singh, J., Winberg, J., Brady, M., Clough, Y. (2024) Farmers' motivations to cultivate biomass for energy and implications. *Energy Policy*, 193, 114295.

Author contributions

Chapter I

All authors contributed to the conceptualisation of the study. **JW** designed the methodology and performed the data collection and analysis, with input from HGS and JE. **JW** wrote the first manuscript draft and all authors contributed with revisions and comments.

Chapter II

All authors conceived the idea of the study. **JW** designed the methodology and performed the statistical analyses with input from LE, HGS, and JE. **JW** wrote the first manuscript draft and all authors contributed with revisions and comments.

Chapter III

All authors contributed to the conceptualisation and design of the study. **JW** carried out the data collection and the statistical analysis with input from HGS and JE. **JW** wrote the first manuscript draft and all authors contributed with revisions and comments.

Chapter IV

JW, HGS, and YC conceptualised the study. **JW**, HGS, JE, and CL designed the methodology. CL performed the agent-based modelling with input from **JW**. **JW** made the agent-based modelling results spatially explicit. MS performed the ecological modelling in discussion with **JW**. Data analyses were made by **JW** with input from HGS and JE. **JW** led the drafting of the manuscript with input from all co-authors.

Authors: Josefin Winberg (JW), Henrik G. Smith (HGS), Johan Ekroos (JE), Lars Eklundh (LE), Yann Clough (YC), Cecilia Larsson (CL), Martin Stjernman (MS)

Abbreviations

ABM	Agent-based model
ANC	Areas of Natural Constraints
BECCS	Bioenergy with carbon capture and storage
CAP	Common Agricultural Policy
EU	European Union
FBI	Farmland Bird Index
GHG	Greenhouse gases
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
LU/LC	Land use/land cover
RED	Renewable Energy Directive
SDG	Sustainable Development Goals
SNG	Semi-natural grasslands
SNH	Semi-natural habitat
SOC	Soil organic carbon

Introduction

Despite humanity's dependence on nature, we are severely altering ecological systems to a point where the quality of life for people is threatened. Human activities have changed biophysical and biochemical systems and processes, driving planetary environmental conditions into a state outside of the safe operating space for humanity (Richardson et al., 2023). Two main factors in the stability and functioning of the Earth system are climate change and biodiversity loss (Steffen et al., 2015). Through our use and transformation of ecosystems, biodiversity is declining globally at an unprecedented rate and currently threatening more than 1 million species with extinction (Díaz et al., 2019; IPBES, 2019; Jaureguiberry et al., 2022). In addition, human-caused climate change poses a threat to humans and nature by affecting the weather and climate extremes across the globe (IPCC, 2023). One of the main challenges for humanity in the 21st century is to find sustainable climate mitigation and biodiversity conservation strategies (IPBES, 2019; IPCC, 2023), a challenge that becomes increasingly urgent. However, a critical question remains: Can we mitigate climate change without harming biodiversity and ecosystems? A large focus in climate mitigation is on energy generation and there are multiple pathways to reduce greenhouse gas emissions in the energy sector. These mainly include replacing fossil fuels with renewable energy sources, such as wind, solar, or biomass energy generation, but few of these options include co-benefits for biodiversity protection (Pörtner et al., 2023). A narrow focus on emission reductions and short-term mitigation solutions carries the risk of generating new sustainability issues, but measures that are locally adapted, holistic, and have a long-term view can create robust and synergistic mitigation pathways (Smith et al., 2022). Moving forward, we need sustainable management of land resources, where climate mitigation occurs in a socially and ecologically responsible manner (Kiesecker et al., 2024) to ensure that no Sustainable Development Goal (SDG) is reached at the expense of another (United Nations, 2015). This requires integrated approaches focusing on the connections, synergies and trade-offs between societal goals. Nexus approaches enable the evaluation of sustainability impacts in complex systems by addressing the interlinkages between sectors and SDGs (Liu et al., 2018), such as providing renewable energy without compromising food production, environmental quality, and biodiversity conservation. In this thesis, I have used a nexus approach to address how different methods of adopting agricultural bioenergy as climate mitigation strategies in Sweden may affect the supply of ecosystem services and biodiversity.

The link between biodiversity loss and climate change

The term biodiversity captures the variability of all organisms, including the diversity within species, between species, and of ecosystems (Convention on Biological Diversity, 1992). In addition to the intrinsic value of ecosystems and all living organisms, i.e. their inherent worth independent of how useful they are to humans (Redford & Richter, 1999), biodiversity also has an instrumental value for humans, including pools and fluxes of materials and energy. Biodiversity loss diminishes these services by altering the ecosystem functions and stability (Cardinale et al., 2012; Isbell et al., 2017). A continued supply of ecosystem functions and resilience that benefit humanity also in the future hence requires conservation of the biodiversity that underpins these ecosystem services (Dee et al., 2019; Mace et al., 2012; Reich et al., 2012).

The conservation of biodiversity and ecosystem services is under additional threat from climate change (Pörtner et al., 2021). Anthropogenic emissions of greenhouse gases (GHG) have resulted in global warming above 1.1°C relative to preindustrial levels, creating additional stresses on human livelihoods, land resources (IPCC, 2023), and nature (Trisos et al., 2020; Urban, 2015). A changing climate forces species to adapt or to shift geographical range, leading to changes in species interactions, composition, and ecological functions (Pörtner et al., 2023). When species cannot migrate to new habitats or adapt to new climate conditions, they may face local or global extinctions (Román-Palacios & Wiens, 2020). Urgent conservation actions are required to maintain a healthy planet for all living species, but the shared drivers and mechanistic links between biodiversity and climate have increased the recognition that a more integrated approach is needed to find sustainable solutions (Pettorelli et al., 2021; Pörtner et al., 2021).

To limit global warming well below a 2°C increase from pre-industrial levels, in line with the Paris Agreement on Climate Change, major reductions of GHG emissions are required worldwide (IPCC, 2023). As a part of the European Green Deal, the European Union (EU) and its member states have set out to reduce GHG emissions by at least 55% by 2030 from 1990 levels and achieve climate neutrality by 2050 (European Commission, 2020b). After the COVID-19 pandemic and the Russian invasion of Ukraine, ensuring energy security within the EU has gained even more importance, thereby reducing the dependency on energy imports (Mišík & Nosko, 2023). This has been concretised in the RePowerEU plan, aligning climate mitigation targets with an energy independence strategy, where actions such as reducing overall energy consumption and increasing the share of renewable energy have been advocated (European Commission, 2022).

At the same time, the EU has adopted a Biodiversity Strategy for 2030 to protect and restore biodiversity and halt ecosystem degradation as a contribution to the Kunming-Montreal Global Biodiversity Framework (European Commission,

2020a). The strategy recognises the interdependence between biodiversity loss and climate change, intending to protect at least 30% of land in Europe and reach the legally binding target to restore at least 20% of degraded land and sea areas under the Nature Restoration Law. The proposed conservation actions are expected to have co-benefits for climate mitigation, in particular by avoiding deforestation and restoring ecosystems with significant carbon storage potential (Shin et al., 2022). Aligning and fulfilling the climate and biodiversity commitments is essential to achieve the transformative change needed to secure healthy ecosystems and a liveable planet (Pörtner et al., 2023).

The focus on agricultural landscapes

Agriculture plays a crucial role in modern society by providing food and biobased material to a growing global population and by supporting rural livelihoods. With more than one-third of all terrestrial land currently devoted to agricultural production, agroecosystems also greatly impact biodiversity and ecosystem functions (IPBES, 2019). In most parts of the world, agricultural productivity has increased rapidly over the last century through developments in the use of synthetic fertilisers, pesticides, machinery, and species varieties (Pellegrini & Fernández, 2018; Robinson & Sutherland, 2002). Despite the increase in agricultural productivity, around 30% of the global population faces food insecurity, with large inequalities between regions (FAO et al., 2023). In addition, intensified agricultural production has resulted in simplified landscapes with increased erosion, soil carbon loss, nutrient run-off, and pollution, which have caused environmental impacts such as eutrophication, soil degradation, global warming, and declines in biodiversity (Power, 2010). Consequently, essential ecosystem services important for agricultural production, such as pollination, biological pest control, nutrient cycling, and soil formation, have declined across intensive agricultural regions (IPBES, 2019). Further land-use intensification may temporarily compensate for some of the productivity reduction caused by declines in ecosystem services but with the risk of additional environmental externalities and productivity loss over time (Seppelt et al., 2019).

Increasing landscape and crop heterogeneity across spatiotemporal scales has been suggested to support biodiversity within agroecosystems (Benton et al., 2003; Fahrig et al., 2011), which in turn may benefit the delivery of ecosystem services (Tscharntke et al., 2005, but see Birkhofer et al., 2018). The increase or maintenance of landscape complexity often involves protecting and restoring semi-natural habitats (SNH) (Gonthier et al., 2014; Holland et al., 2017), while crop diversification in space and/or time from e.g. intercropping or crop rotation can contribute to complexity at the field level (Hufnagel et al., 2020). SNH, such as field edges, woodlands, or extensive grasslands, are important habitats for several

organisms, including pollinators and natural enemies that may spill over to surrounding sites and have a positive spillover effect for pollination and pest control in the agricultural landscape (Blitzer et al., 2012; Holland et al., 2017; Öckinger & Smith, 2007). The connectivity between suitable habitats influences the dispersal of species among habitat patches, where the importance of the scale of connectivity is set by the behaviour and characteristics of the organism (Taylor et al., 2006).

Agricultural land can be both a source and sink of carbon due to anthropogenic and natural factors. With the agricultural sector accounting for more than 10% of anthropogenic GHG emissions, there is great potential for adopting land uses, agricultural practices, and food systems that contribute to climate mitigation and adaptation (IPCC, 2019). However, there are major concerns that agricultural mitigation could negatively affect the food and biomass supply (Smith et al., 2013; Valin et al., 2013), which calls for mitigation strategies that reduce the trade-off between GHG abatement and food security. Within agricultural production, such proposed strategies include for example increased sequestration of soil organic carbon (SOC) on cropland (Frank et al., 2017), sustainable intensification (Pretty & Bharucha, 2014; Rockström et al., 2017), or optimised input of mineral fertilisers (Foley et al., 2011). Together with the reduction of food waste and losses throughout the post-harvest production chain (Notarnicola et al., 2017; Vázquez-Rowe et al., 2021), and dietary shifts towards products with a lower GHG footprint (Aleksandrowicz et al., 2016; Tilman & Clark, 2014), food production could be maintained while fundamentally reducing the environmental impact.

In parallel with the intensification and regional specialisation of agriculture in Europe, an increased abandonment of marginal or remote arable land and semi-natural grasslands has been recorded (Ustaoglu & Collier, 2018). The cessation of agricultural activities and management has been attributed to biophysical, socioeconomic, and political factors that limit the profitability of maintained production in certain fields or regions (MacDonald et al., 2000; Rey Benayas et al., 2007; van der Zanden et al., 2017). Farmland abandonment may further exacerbate the competition over limited resources of arable land that already faces increasing demand for agricultural commodities, environmental consideration, and biodiversity conservation (Lécuyer et al., 2021). At the same time, abandoned land is also seen as a promising resource for alternative uses to avoid land-use conflicts (Muscat et al., 2022). If abandoned farmland does not remain abandoned for natural succession to revegetate the former fields towards semi-natural landscapes, it is often afforested, urbanised, or transformed back to agricultural use (Fayet et al., 2022).

The environmental impacts of farmland abandonment are context-dependent and can further be influenced by site characteristics, former land use, and the surrounding landscape (MacDonald et al., 2000; van der Zanden et al., 2017). Abandonment in intensively farmed agricultural landscapes may offer opportunities for regenerating natural ecosystems that can enhance the local and landscape

heterogeneity, increase SOC sequestration, and reduce the use of chemical inputs (Navarro & Pereira, 2012; van der Zanden et al., 2017). On the contrary, abandoning fields in low-intensity traditional farmland landscapes can cause negative environmental and ecological impacts as they are dependent on the extensive management that has shaped unique conditions for biodiversity and ecosystem services over hundreds or even thousands of years (MacDonald et al., 2000; Queiroz et al., 2014). When considering abandoned land for alternative uses, studies that consider both local and landscape context-specific conditions are necessary to avoid further land-use conflicts.

Agricultural landscapes have undergone considerable changes over the past centuries, and Sweden is no exception. In the high-productive arable regions fields have become larger and more intensely managed, while landscape openness has decreased in the marginally productive regions due to afforestation (Ihse, 1995). Furthermore, more than 50% of grasslands with a long history of extensive grazing and mowing, so-called semi-natural grasslands (SNGs), have been lost over the past 100 years due to reduced number of cattle, arable intensification, afforestation, or abandonment (Aune et al., 2018; Swedish Board of Agriculture, 2008). SNGs are often characterised by a high biodiversity consisting of species adapted to and dependent on biomass removal from grazing and mowing (Eriksson et al., 2002). The loss of grasslands from Swedish landscapes has not only resulted in a decline in biodiversity (Cousins, 2009), but likely also in a loss of ecosystem functionality as SNGs are important for ecosystem services such as carbon storage, pollination, and erosion control (Bengtsson et al., 2019).

Even if other open habitats similar to SNGs in the boreal landscape can serve as alternative habitats for grassland species (Andersson et al., 2022; Johansen et al., 2022), the surrounding landscape has successively become less suitable for most grassland species to survive. Increasing demand for forest products has driven the intensification of Swedish forestry, resulting in a forest landscape dominated by even-aged stands of monocultural spruce plantations, managed in rotational clear-felling (Petersson et al., 2019). The land use within agriculture and forestry, including deforestation and the increasing overgrowth of abandoned land, are the main factors driving the red-listing of species in Sweden (Eide et al., 2020).

With a growing population to feed (Godfray et al., 2010), higher demand for biobased material (Muscat et al., 2020), and an urgent need for climate mitigation and biodiversity conservation (Pörtner et al., 2021), the agricultural landscape is under higher pressure than ever. When selecting the pathway forward, research and policy must focus on identifying synergies between these demands and how these can be balanced in different landscape contexts.

Bioenergy – a sustainable source of renewable energy?

The main source of renewable energy in the EU is bioenergy produced from agricultural, forestry, and organic waste feedstock, accounting for around 60% of the renewable energy consumption (European Commission, 2023). To meet the global and European GHG reduction targets, bioenergy coupled with carbon capture and storage (BECCS) is expected to play an important role also in the future energy supply (European Commission, 2017; Rogelj et al., 2018) by offering opportunities for domestic energy markets and a predictable energy supply to sectors that are difficult to decarbonise or electrify (Davis et al., 2018; Debnath et al., 2019). The current main utilisation of bioenergy is for heating and cooling, but biomass is also used to produce biofuels and bioelectricity (European Commission, 2023). Sweden is one of the countries in the EU that has the largest supply and per capita consumption of bioenergy (Wu & Pfenninger, 2023), with forest biomass accounting for more than 80% of the utilised bioenergy (Black-Samuelsson et al., 2017). While Swedish forestry mainly supplies wood for pulp and timber, the residues from harvests and industries (e.g. slash, stumps, and sawdust) are important for bioenergy production. However, the sustainability of forest-derived bioenergy has been questioned because of the negative impacts on biodiversity and uncertain GHG emission reductions of the current silvicultural production system and intensive forest management (de Jong & Dahlberg, 2017; Harper et al., 2018; Norton et al., 2019). The ongoing climate change is putting further pressure on the Swedish forests to provide increased harvests of wood for supplying bioenergy and biobased materials for the decarbonisation of society (Cintas et al., 2017; Hildebrandt et al., 2017), at the same time as the importance of sustainable forest management to enhance carbon storage in forests has been emphasised (IPCC, 2019). The impossible task of managing forests to maximise both the carbon storage and the harvest of forest biomass to substitute fossil fuels within the same timeframe (Rummukainen, 2021) suggests other sources of biomass, such as agricultural feedstock, are needed for future bioenergy production (Searchinger et al., 2022).

The first generation of agricultural bioenergy crops was derived from oils, starches, and sugars of food biomass, such as wheat, corn, or oil crops. These crops were mainly used to produce biofuel but because of their direct competition with food production and negative effects on biodiversity, attention has been turned to second-generation bioenergy crops (residues or lignocellulosic, woody crops) (Havlik et al., 2011; Immerzeel et al., 2014). However, the choice of biomass matter is not the only factor important for ensuring emission reductions from bioenergy, but also the land used for biomass production and how the energy is being used (Harper et al., 2018). Cultivation of bioenergy crops on agricultural land risks indirect land-use changes and displacement effects on GHG emissions and biodiversity, as additional land is needed to maintain food production (Nunez-Regueiro et al., 2019; Searchinger et al., 2008). In addition, the context-specific biophysical and socio-economic

conditions may increase the risk of land degradation, displacement of local actors, food insecurity, water scarcity, and biodiversity loss (IPCC, 2019; Vera et al., 2022). The controversial sustainability implications of agricultural bioenergy have been debated for the past decades (Leemans et al., 1996; Robledo-Abad et al., 2017; Tilman et al., 2009), leading to increasingly ambitious sustainability requirements for bioenergy to minimise trade-offs between energy production, food security, and the protection of the environment. For energy used within the EU, these requirements are specified in the EU Renewable Energy Directive (RED) (EU Directive 2023/2413) and include for example restrictions on using biomass that undermines food and feed production, land carbon sinks, or biodiverse habitats, with GHG emissions saving criteria for the energy that is produced.

One alternative source of bioenergy that reduces environmental trade-offs as well as competition over land and food is the energy production from municipal waste and residues from agriculture and forestry (Vera et al., 2022). However, the supply of residues does not meet the full demand for bioenergy (Daioglou et al., 2019) which has created a growing body of literature that investigates the potential to integrate perennial energy crops strategically in the agricultural landscape to mitigate the negative impacts of intensive agriculture (Asbjornsen et al., 2014; Carlsson et al., 2017; Dauber & Miyake, 2016; Englund et al., 2020a; Milner et al., 2016), or to produce dedicated bioenergy feedstock on marginal or abandoned cropland (Dauber et al., 2012; Muscat et al., 2020; Næss et al., 2023).

Marginal land is a wide term, often used to describe low-productive or remote land in the agricultural landscape that is on the economic margin for food or feed production (Elliott et al., 2024; Shortall, 2013; Tilman et al., 2006). The marginality of land may be defined due to the biophysical characteristics of the land (such as the soil quality or erodibility) (Gelfand et al., 2013; Gopalakrishnan et al., 2011), the utilisation (Dale, 2010; Gopalakrishnan et al., 2011; Shortall, 2013), the geographical location (Beilin et al., 2014; MacDonald et al., 2000), or the socio-economic setting (Khanna et al., 2021; Strijker, 2005). Driven by the limited economic viability or any other factors that hinder production, marginal arable fields or grasslands risk abandonment if no incentives are in place to maintain the production (Elliott et al., 2024; Munroe et al., 2013). Marginal and abandoned land have received wide attention for the potential to produce bioenergy crops that thus will not compete with food production at the same time as it provides an alternative source of income for rural communities as the perennial energy crops often are better adapted to poor production conditions (Khanna et al., 2021; Mehmood et al., 2017). Depending on the characteristics of the site and land owner preferences, marginal or abandoned land may be used for the production of agricultural feedstock or forest biomass to generate bioenergy (Csikós & Tóth, 2023). However, the feasibility of cultivating bioenergy crops on marginal land has been questioned due to low economic incentives (Bryngelsson & Lindgren, 2013), poor yields (Dauber et al., 2012), and limited willingness from farmers to supply marginal land for

bioenergy crop production (Skevas et al., 2016). Many types of marginal land may also have alternative use values, such as sequestering carbon or providing valuable sites for biodiversity conservation or recreational activities (Dauber et al., 2012; Gopalakrishnan et al., 2011) that have to be taken into account before being considered for biomass production.

While utilisation of marginal land for bioenergy production does not fully resolve sustainability trade-offs, growing perennial energy crops on marginal land or in intensively farmed landscapes can reduce environmental problems such as erosion, nutrient leakage, and flooding (Englund et al., 2020a), as well as increasing SOC sequestration (Carlsson et al., 2017; Xu et al., 2022). If bioenergy systems are developed sustainably, they could increase the multifunctionality of agroecosystems to promote synergies between bioenergy production, biodiversity, and the provisioning of ecosystem services (Carlsson et al., 2017; Englund et al., 2023). In the Nordic countries, including Sweden, one such strategy is including perennial grass in crop rotations with annual crop production (Englund et al., 2023; Prade et al., 2017). Growing grass leys for feed and pastures is a common practice in Sweden, where nearly half of the agricultural land presently is used for grass ley production (Swedish Board of Agriculture, 2023b), but the same biomass could also be used as a biogas substrate (Ahlgren et al., 2017; Gustafsson & Anderberg, 2023).

Marginal and abandoned land, as well as additional integration of grass leys in intensive agriculture, could play an important role in increasing the domestic bioenergy supply in Sweden, but more knowledge is needed on how such climate mitigation strategies may impact ecosystem services and biodiversity across spatial scales. This thesis contributes with new aspects to the overarching question of how Swedish agricultural landscapes could be used for sustainable bioenergy production without compromising the supply of ecosystem services and biodiversity.

Thesis aims and scope

This interdisciplinary thesis aims to increase the knowledge of sustainable bioenergy production from the Swedish agricultural landscape and to understand the challenges and opportunities of increased agricultural bioenergy production for other societal goals. To achieve this goal, I have studied the interaction between bioenergy strategies, ecosystem services supply, and biodiversity conservation, where sustainable land use is a central focus. The thesis evaluates different pathways to sustainable bioenergy by covering multiple alternative production sites and biomass sources (Figure 1). First, I provide an overview of the sustainability and research gaps in agricultural bioenergy (**Chapter I**). I then address two strategies for sustainable bioenergy production: i) using abandoned or marginal land to produce bioenergy to avoid conflicts with food production (**Chapters II and III**), and ii) integrating grass biomass production in the intensive agricultural landscape as a multifunctional climate mitigation action (**Chapter IV**).

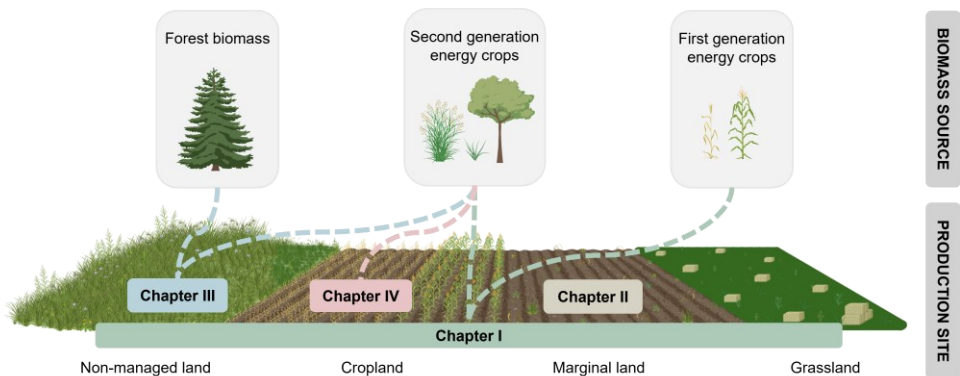


Figure 1. A conceptual overview of the biomass sources and production sites in focus of the different chapters of the thesis. Image source: BioRender.com

For each of the chapters I addressed the following research questions and aims:

Chapter I: *How does introduction of bioenergy crops on different types of agricultural land impact the supply of ecosystem services and biodiversity?*

In Chapter I, I give an overview of the sustainability of agricultural bioenergy by reviewing the impact of bioenergy-driven land-use changes in temperate agricultural landscapes on ecosystem services and biodiversity. The literature review was limited to only considering studies of land conversions that have been suggested within policy and/or research as potential production sites for agricultural bioenergy (arable land, grasslands, marginal land, abandoned land, and fallows), and I included both first- and second-generation bioenergy crops. The aims of Chapter I were to i) identify potential synergies or trade-offs between biodiversity conservation and ecosystem services from the studied land-use changes, ii) analyse patterns in how bioenergy land-use changes are studied and how this may impact the interpretation of results, and iii) identify research gaps for how an introduction of bioenergy crops in the agricultural landscape impacts biodiversity and ecosystem services. The findings from Chapter I guided the aims of the following chapters to cover research gaps and uncertainties in Swedish and European bioenergy research.

Chapter II: *To what extent can easily identified marginal land contribute to sustainable bioenergy production?*

In Chapter II, I studied marginal land in south Swedish arable landscapes to improve the understanding of its potential for bioenergy production. Using public databases, I mapped, quantified, and characterised marginal land, and with the aid of remote sensing I identified the current land use. The aims of Chapter II were to i) understand what type of marginal land can be identified from public databases, ii) study how marginal land differs from productive arable land in biophysical characteristics and socioeconomic settings, and iii) assess potential alternative use values of marginal land and how these may affect the availability for feedstock cultivation.

Chapter III: *What are the biodiversity consequences of using abandoned grasslands for bioenergy production?*

Chapter III builds further on the findings from Chapters I and II by focusing on land-use changes of SNG in a mixed farm-forest region of south Sweden that is sensitive to agricultural abandonment. Using a space-for-time substitution approach, I studied how plant communities of SNG respond to three land-use change scenarios: grazing abandonment, spruce afforestation, and grassland improvement by intensification. The aims of this chapter were to i) evaluate the contribution of abandoned, afforested, and improved SNG to local plant diversity, and ii) assess what effects an increased production of wood and grass for bioenergy purposes on abandoned SNG could have on biodiversity.

Chapter IV: *Can the integration of agricultural bioenergy production in intensive cropping regions act as a multifunctional climate mitigation strategy?*

Finally, in Chapter IV, I studied the potential of agricultural bioenergy production as a multifunctional climate mitigation strategy in intensively farmed regions. Focusing on grass leys for bioenergy production and using an agent-based model

(ABM) in combination with an ecological model on farmland bird diversity, this chapter aimed to i) assess how incentivising energy ley production affects the farm structure and land use in an intensive cropping region, and ii) evaluate how increased uptake of energy ley in crop rotations affects the supply of ecosystem services and conservation of farmland birds.

Methods

Study systems and data collection

This thesis is set in the agricultural landscape and includes land-use studies for bioenergy production across spatiotemporal scales. **Chapter I** gives an overview of bioenergy-driven land-use changes of agricultural land in the temperate climate zone using literature from North America and Europe, and **Chapters II, III, and IV** study the potential for and impacts of producing agricultural bioenergy in southern Sweden (Figure 2).



Figure 2. Maps of the spatial extent of the study systems in the four chapters. Chapter I reviewed studies from the temperate climate zone (illustrated in turquoise). For Chapters II-IV, the study systems are illustrated with a background map sourced from OpenStreetMap. Chapter II included the nine southernmost counties in mainland Sweden, Chapter III focused on 42 field sites in Jönköping county, and Chapter IV studied the production region GSS (Göteborgs Södra Slättbygd).

In **Chapter I**, a literature review was conducted to synthesise the biodiversity and ecosystem service impacts from land-use changes to bioenergy production in temperate agroecosystems (Figure 2). The search for literature was performed in the Web of Science Core Collection to access peer-reviewed research articles, using methods for systematic reviews to reduce biases (Haddaway et al., 2015). The literature search was based on a pre-determined search string and the identified papers were screened for relevance with a decision tree, resulting in 54 original research papers in the review. A review matrix was used to extract the relevant information from each article, including details of the reference land use, bioenergy crop, taxonomic group to represent biodiversity, examined ecosystem service(s), geographical scope, methodology used, production scale, and the assessed impact (on the species, taxonomic group, or ecosystem service). Studies were subdivided into land-use change cases to synthesise how specific land-use changes affected individual ecosystem services or taxonomic groups. The reference land use was categorised into four groups: arable land, grassland, marginal land, and non-managed land, and bioenergy crops were grouped into first- or second-generation energy crops. The categorisation of ecosystem services was based on the Millennium Ecosystem Assessment classification (Millennium Ecosystem Assessment, 2005), and the biodiversity assessments were classified into taxonomic groups: amphibians, birds, reptiles, mammals, invertebrates, plants, microorganisms and, in cases where no explicit organism was studied, unspecified biodiversity. The methodology used in the reviewed literature was grouped into direct (empirical) and indirect (modelling, simulations) measurements, and the geographical scope was categorised into local and regional scales. For each land-use change case, the assessed impact on a specific ecosystem service or species/taxonomic group from the literature was noted as positive, neutral/mixed, or negative.

Chapter II focused on the nine southernmost counties of mainland Sweden to identify and characterise marginal land. The nine counties (Skåne, Blekinge, Kronoberg, Halland, Kalmar, Jönköping, Örebro, Östra Götaland, and Västra Götaland; Figure 2) contain the majority of agricultural land in Sweden but differ in land-use intensity, landscape complexity, and socioeconomic conditions. The present utilisation of land was used as an indicator to detect marginal land that either had no evident uses or was used in arable production but without receiving agricultural subsidies. In a raster-based analysis, we developed a spatial analysis funnel approach to identify marginal land from land-use and land cover data from official databases (Lantmäteriet, 2021; Statistics Sweden, 2021; Swedish Board of Agriculture, 2021; Swedish Environmental Protection Agency, 2020, 2021; Swedish University of Agricultural Science (SLU), 2015; The Swedish Transport Administration, 2021). The analysis started from the broad land-cover classes “Agricultural land” and “Open land with vegetation” in the National Land Cover Database of Sweden and from these two classes all other apparent land uses were removed, including arable land that received any CAP subsidies during 2015-2020,

forested land, urban areas, military areas, recreation facilities, nature protected areas, infrastructure, buildings, and waterfronts by oceans, lakes, or rivers. All connecting raster cells larger than 0.1 ha were kept for further evaluation of the marginal land availability for bioenergy production.

In **Chapter III**, we conducted a space-for-time substitution study (Pickett, 1989) to assess the potential biodiversity effects of biomass production on abandoned grasslands in a mixed farm-forest study area in southern Sweden (Figure 2). The study area was located in Jönköping county (57°45'N, 14°12'E), a forest-dominated region with agricultural landscapes mainly consisting of animal farms and small holdings that are susceptible to farmland abandonment (Perpiña Castillo et al., 2018). We identified 42 sites of grazed, abandoned, spruce afforested, and improved SNG, using agricultural and forest land-use data (Swedish Board of Agriculture, 2021, 2022; Swedish Environmental Protection Agency, 2020) and times-series of orthophotos (Lantmäteriet, 2022). Plant surveys were conducted in two survey rounds between June and August 2022 to identify vascular plants to species level for each site (Figure 3). The sampling was randomly distributed along site borders and within the site to achieve a similar sample completeness for all sites and habitats (Chao & Jost, 2012).



Figure 3. Field assistants and the author conducting plant surveys in grazed semi-natural grassland (to the left) and afforested semi-natural grassland (to the right). Photos taken by author (2022).

For **Chapter IV** we combined agent-based economic modelling with multiple ecosystem services and biodiversity production functions to estimate the consequences of policies incentivising energy leys as a climate mitigation strategy. The combined assessment of ecosystem services and biodiversity under different

policy and land-use scenarios allowed the identification of synergies or trade-offs between different outputs and societal goals (cf. Nelson et al., 2009). The study focused on Götalands Södra Slättbygder (GSS, i.e. the arable plains of southern Sweden; Figure 2), the most productive arable region in Sweden that extends over the two counties Skåne (55°59'N, 13°26'E) and Halland (56°43'N, 12°49'E).

Data analysis

After using a systematic approach to identify and classify relevant literature for the literature review in **Chapter I**, we summarised the land-use change cases into a total impact assessment for specific taxonomic groups or ecosystem services following Immerzeel et al. (2014). The total impact included five classes: 1) strong positive impact ($\geq 75\%$ of the cases reported a positive impact), 2) moderate positive impact ($\geq 50\%$ but $< 75\%$ of cases reported a positive impact), 3) no or mixed impact (no impact or equally many cases with positive and negative impacts), 4) moderate negative impact ($\geq 50\%$ but $< 75\%$ of cases reported a negative impact), or 5) strong negative impact ($\geq 75\%$ of the cases reported a negative impact).

The marginal land identified in **Chapter II** was characterised by analysing the land use/land cover (LU/LC), soil moisture, crop productivity, and socioeconomic setting, to assess the type of marginal land that may be identified from public databases and its potential for bioenergy production. The LU/LC was determined for a subset of the marginal land using remote sensing (Google, 2022; Lantmäteriet, 2022). We also identified the land cover surrounding these sites (Swedish Environmental Protection Agency, 2020) to identify in which landscapes marginal land generally occurs. The same subset of marginal land was used to compare the soil moisture index (Swedish Environmental Protection Agency, 2020) of marginal land to the surrounding 1 km arable landscape using a Wilcoxon signed-rank test and to existing energy crop sites using a Mann-Whitney U test. The relationship between marginal land and site productivity was analysed using generalised linear models with the standard yield of spring barley across crop yield areas from Swedish Board of Agriculture (2023a) as the dependent variable. The analysis was weighted by the influence of organic farming on yields and the geographical coordinates were added as fixed terms to the model to account for spatial autocorrelation in the model residuals. Further analysis of how the farming conditions (regional productivity and socioeconomic setting) were associated with the area of marginal land identified was made by comparing marginal land coverage across areas of natural constraints (ANCs) using a Kruskal-Wallis rank-sum test.

In **Chapter III**, we investigated the impact of biomass production on abandoned grasslands for local plant diversity and community composition. To analyse local

diversity, generalised linear models were constructed with species richness and Shannon diversity as response variables and habitat type, landscape composition in a 1 km radius of each site, time since land conversion/abandonment, and sampling intensity as predictors. The difference in plant community composition between habitats and its relationship to SNG coverage in the surrounding landscape was analysed using nonmetric multidimensional scaling (NMDS) ordination analysis and permutational multivariate analysis of variance (PERMANOVA). The community dissimilarity was further analysed by calculating its turnover and nestedness components to assign the dissimilarity pattern to species replacement or species loss (Baselga, 2010). Species of conservation concern were identified using information on red-listing, signal species, and/or protected species (SLU Art databanken, 2023).

In **Chapter IV**, the ABM AgriPoliS (Happe et al., 2006) was used to simulate how farm structure and land use responded to three policy scenarios differentiated by increasing area-based subsidies to the production of energy leys for biomethane (50, 200, and 350 € ha⁻¹). These were compared to a reference scenario where the subsidy for energy ley was set to zero. From the AgriPoliS model and the submodels coupled to it, we also extracted information on soil carbon content (% SOC in topsoil; Brady et al., 2019), pesticide use (kg active substance of fungicides, herbicides, and insecticides; Agriwise, 2017), and contribution to food production (kcal produced from food crops, meat, and dairy; Boke Olén et al., 2021). To assess ecological consequences contingent on landscape configuration on fine spatial scales, the AgriPoliS model output was extended from a simple landscape representation to spatially explicit results, using the farm typology of GSS (Boke Olén et al., 2021) and spatial agricultural information from the Integrated Administration and Control System (IACS) database. The resulting land-use maps with detailed crop information were used to predict farmland bird diversity impacts, using the estimates of relationships from a joint-species distribution model (Hristov et al., 2020; Stjernman et al., 2019). The predicted farmland bird abundance was aggregated to species-specific regional abundances for each scenario and normalised by dividing the regional abundance in the energy ley scenario by the corresponding value in the reference scenario, to ultimately calculate a composite farmland bird index (FBI) following the method of Gregory et al. (2005).

Results and discussion

Sustainability of agricultural bioenergy

Strategies to increase the sustainability of agricultural bioenergy have revolved around the land-use changes surrounding biomass production (Dauber et al., 2012; Tilman et al., 2009; Valentine et al., 2012), but few studies have considered the combined impact of these strategies on ecosystem services and biodiversity. **Chapter I** provides an overview of how ecosystem services and biodiversity are affected under bioenergy-related land-use change scenarios suggested by policy and research. We found that agricultural bioenergy research is highly segregated between those focusing on ecosystem services and those focusing on biodiversity, with a predominance of the former (Figure 4). This raises concern about the policy recommendations given by bioenergy research, not only because of the risk for biodiversity loss but also because biodiversity and many ecosystem services are highly interlinked such that a loss of biodiversity could diminish ecosystem services important for agriculture (Le Provost et al., 2023). Furthermore, our results show that the cultivation of bioenergy crops in the agricultural landscape comes with two main trade-offs, either for food production or for biodiversity conservation. Despite the risk of decreased food security due to displacement effects, deploying perennial energy crops on arable land is widely researched and our review shows that this strategy has the potential to reduce the negative environmental and ecological impacts of intensive agriculture. Several previous studies have shown similar results (e.g. Dauber et al., 2010; Englund et al., 2020b; Werling et al., 2014), highlighting the potential role of feedstock cultivation on arable land as a multifunctional strategy to mitigate climate change.

To alleviate the competition with food production, biomass production on marginal land or abandoned land has been promoted as a sustainable bioenergy alternative (Gelfand et al., 2013; Gopalakrishnan et al., 2011; Vera et al., 2022), however, the results of **Chapter I** suggest that few studies have assessed the environmental and ecological impacts of using non-managed land for agricultural bioenergy production (Figure 4). In addition, we identified a large knowledge gap on the ecological implications of cultivating energy crops on marginal land, with the few studies focusing on biodiversity impacts predominantly reporting negative effects. Bioenergy production from marginal or abandoned land could hence be in direct conflict with biodiversity conservation (Plieninger & Gaertner, 2011), emphasising

the importance of a joint recognition of ecosystem services and biodiversity for bioenergy-related land-use changes in future strategies for and research on agricultural bioenergy to avoid trade-offs between different societal goals.

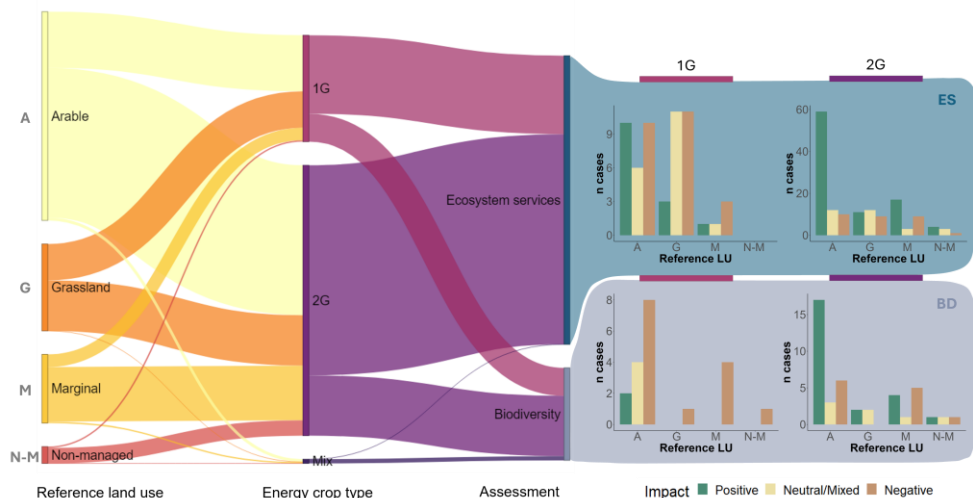


Figure 4. Overview of the reviewed literature in Chapter I, showing reference land use, energy crop type, assessment type, and impact. Starting from the left, the Sankey diagram shows the division of reference land uses that were included in the reviewed literature, the land use change to energy crops (first generation (1G) annual food crops, second generation (2G) perennial crops, or a mix of the two (Mix)), the assessment type of energy crops (ecosystem services or biodiversity), and the impact of the assessed land-use changes (number of positive, neutral/mixed, or negative cases). The bar plots on the right show the synthesised impact on ecosystem services and biodiversity for 1G and 2G crops. Abbreviations: ES: Ecosystem services, BD: Biodiversity, A: Arable land, G: Grassland, M: Marginal land, N-M: Non-managed land, 1G: First generation energy crops, 2G: Second generation energy crops, Mix: Mix of 1G and 2G crops.

Biomass production on marginal and abandoned land

To address the existing knowledge gap on the environmental and ecological effects of biomass production on marginal and abandoned land identified in **Chapter I**, we focused on identifying and characterising Swedish marginal land in **Chapter II** and evaluating the biodiversity implication of using abandoned farmland for bioenergy production in **Chapter III**. When studying marginal land, the definition and framing of marginality are central to what type of land will be identified (Csikós & Tóth, 2023; Muscat et al., 2022). Earlier studies of bioenergy potential from marginal land in Sweden have made general production estimates based on official land use data (cf. Börjesson, 2016; Nilsson & Rosenqvist, 2018; Olofsson & Börjesson, 2016; Prade et al., 2017), but without further studies of alternative use values and availability, these assessments are prone to large uncertainties. In **Chapter II** we defined marginal land as unused open land (such as abandoned land) and arable land

outside the agricultural subsidy system. Agriculture without financial support was included in our marginal land definition as it is more sensitive to abandonment (Renwick et al., 2013) and is likely less intensively managed (Brady et al., 2017), which could indicate limitations for cost-effective production. The total area of marginal land identified in the nine Swedish counties ranged from 0.74% of the county area in Jönköping to 1.56% in Skåne (Figure 5). Out of all the marginal land, only a minor share (11%) was without management. The remainder of the land was either unsuitable for biomass production (wetlands or rock surfaces), was already used for biomass production to some extent (managed grasslands, agricultural fields, or tree plantations), or served as pastures for horses or livestock. Assuming all these land types as available for biomass production could compromise alternative use values, such as food production, recreation, or biodiversity conservation.

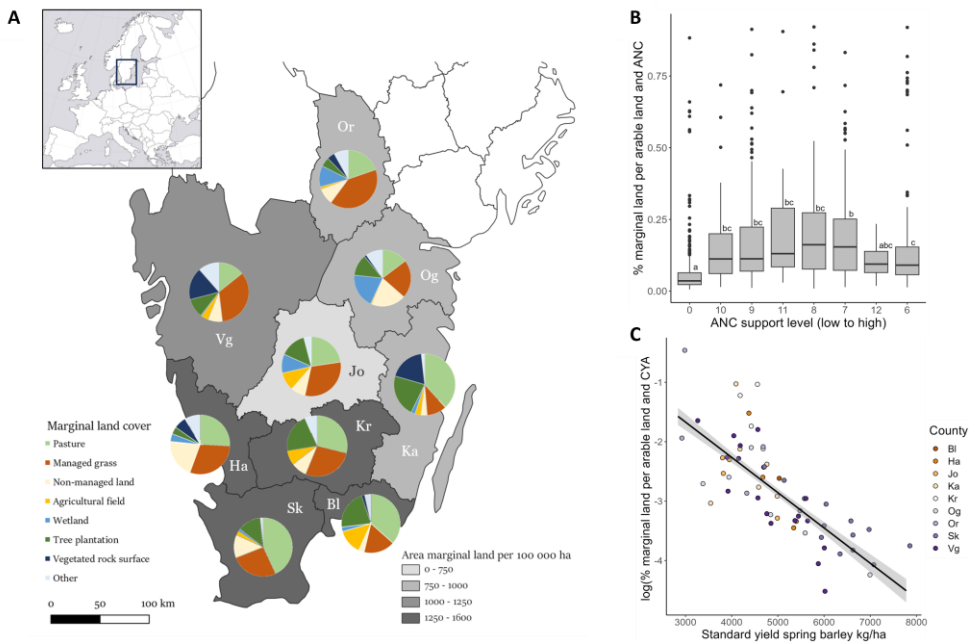


Figure 5. Area, land use, farming conditions, and productivity of the marginal land identified for the nine south Swedish counties in Chapter II. **A)** The total identified area of marginal land and the land use of 200 randomly selected marginal land sites within each county. County abbreviations: Sk: Skåne, Bl: Blekinge, Ka: Kalmar, Kr: Kronoberg, Ha: Halland, Vg: Västra Götaland, Jo: Jönköping, Og: Östergötland, Or: Örebro. **B)** The share of marginal land identified per arable land across ANCs (areas with natural or other area-specific constraints, i.e. farming conditions) and the level of ANC payments (compensatory economic support level). Category 0 has no ANC support (good farming conditions), category 10 has the lowest support, and category 6 has the highest support (constraining farming conditions). **C)** The relationship between the share of marginal land identified per arable area and the standard yield of spring barley across crop yield areas (CYA).

We found that about half of the marginal land were parcels that formerly received agricultural subsidies, but that currently either continued to be agriculturally managed without economic support, had been abandoned, or converted, mainly because of afforestation, infrastructure, or recreation. Even if the highest density of marginal land was identified in high-productive regions, we found a negative correlation between the relative share of marginal land per agricultural area and productivity. Moreover, the marginal land generally consisted of small land parcels (less than 0.5 ha). The small size and lower productivity of the identified marginal land would likely make biomass production difficult and unattractive due to the low cost- and time efficiency (Bryngelsson & Lindgren, 2013; Skevas et al., 2016). The use of marginal land for sustainable bioenergy production is commonly suggested within research and policy, but marginal land is also framed as important for food security, rural development, and ecosystem restoration, resulting in the same competing claims over marginal land as for productive land (Muscat et al., 2022). Improved mapping of marginal land will not remove these competing claims, nor will it change farmers' views of how marginal land could and should be used (Helliwell, 2018; Skevas et al., 2016). Bioenergy production from marginal land could make an important contribution to climate mitigation, however as shown in **Chapter II**, the use of marginal land will not overcome the land-use debate surrounding agricultural bioenergy if alternative use values are not considered.

The findings of **Chapter II** suggested that marginal land mainly occurs in mixed arable-forest landscapes and that a large share of the marginal land is grazed, passively managed, or abandoned SNGs. These results informed the focus of **Chapter III**, in which we studied the ecological implications of using abandoned SNGs for energy biomass production (ley and spruce) in a mixed farmland-forest region of southcentral Sweden. We found that both abandonment, afforestation, and grassland improvement of SNGs reduced local phytodiversity and altered plant communities compared to grazed SNGs, with the most profound negative effects from grassland afforestation and improvement to grass ley production (Figure 6). The difference in species communities was almost entirely explained by species turnover, i.e. species replacement. SNGs are among the most species-rich ecosystems in temperate landscapes with a manifold of rare species dependent on their continued management (Habel et al., 2013), and cessation of grazing or mowing generally affects plant diversity negatively (Elliott et al., 2023; Pykälä et al., 2005). Interestingly, our results showed that abandoned SNGs remain relatively important habitats for grassland species at an early stage of abandonment with similar plant species composition to grazed SNGs (Figure 6B). The abandonment of grasslands however resulted in a loss of rare species and even if there are studies claiming that the natural succession occurring after abandonment could create rewilded semi-natural habitats important for conservation (cf. Navarro & Pereira, 2012), a loss of species richness in grassland habitats could reduce both biodiversity as well as the supply of ecosystem services and the ecosystem multifunctionality (Prangel et al., 2023). However, both local and landscape processes are important

for the structure of plant diversity (Foster, 2001; Schmucki et al., 2012). In addition to the effect of local management, we found that increased coverage of SNG in the surrounding landscape had a positive spill-over effect on plant species richness and Shannon diversity for all habitat types.

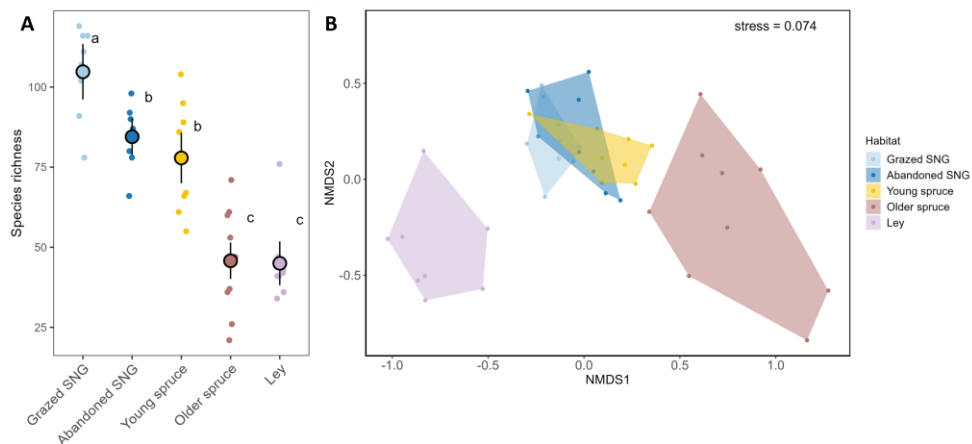


Figure 6. **A)** Observed (smaller coloured points) and predicted (larger filled points) plant species richness for the different habitat types. The letters a, b, and c show significant differences ($p < 0.05$) in predicted species richness between habitats. The habitat types that do not share a letter are significantly different. **B)** The result of a non-metric multidimensional scaling (NMDS) showing the dissimilarity in plant species composition between the surveyed sites, grouped by habitat type.

The results of **Chapter III** highlight the importance of SNGs for local and landscape diversity but also suggest that abandoned grassland may hold high conservation values and should not be seen as available for intensive biomass production by default. Even if it also exists grasslands with low conservation values that could be better suited for biomass production, additional and updated assessments are needed to identify the grasslands with the highest biodiversity values (Larsson et al., 2020). However, despite the risk to grassland biodiversity, abandonment of SNGs is an ongoing process in Sweden (Eriksson et al., 2002), enhanced by dietary shifts (Röös et al., 2016) and increased costs for cattle farming (Söderberg & Hasund, 2021). When grazing is no longer possible, extensive management of abandoned grasslands, such as mowing, offers an opportunity for biomass harvesting that also may contribute to restoring the grassland flora (Heinsoo et al., 2010; Huhta et al., 2001).

In summary, **Chapters II** and **III** overview the availability of marginal land and abandoned land for energy biomass production, suggesting that neither of the two land types offers a simple and unproblematic solution to the increasing demand for biobased energy and material (Hertel et al., 2013). The competition for land is further amplified by climate change (IPCC, 2023) and the growing demand for food

from an increasing population (Barthel et al., 2019), putting additional pressure on all types of land to produce food, feed, fuel, or nature conservation (Muscat et al., 2022). Moving forward, an integrated approach to biomass production, ecosystem service supply, and biodiversity conservation should be a priority to promote bioenergy production that does not compromise other societal needs.



Figure 7. A field with grass ley being harvested. Photo taken by author (2022).

Integrated biomass production in intensive agriculture

In **Chapter IV** we explored an alternative agricultural bioenergy strategy where grass biomass production (grassland ley; Figure 7) is integrated into intensively farmed agriculture as a multifunctional climate mitigation strategy (Carlsson et al., 2017; Englund et al., 2023). In contrast to earlier studies, we wanted to understand how incentivising energy grass production in an intensive cropping region in southern Sweden affects the uptake of energy grass in crop rotations and how the changes in farm structure and land-use change could affect the supply of ecosystem services and biodiversity. By comparing three different subsidy levels for energy ley production to a reference scenario without any such subsidy, our results showed that the total ley production only increased when very high financial incentives were introduced. For the lower payment levels (50 or 200 € ha⁻¹) the increase in energy ley was mainly achieved at the cost of fodder ley, an outcome that could be expected

in productive agriculture with high cereal prices (Ford et al., 2024; Stürmer et al., 2013). In contrast, a subsidy of 350 € ha⁻¹ resulted in 40% of the utilised agricultural area dedicated to ley production, which increased soil carbon storage, reduced pesticide use, and increased the overall abundance of farmland birds, in addition to the generation of substrate for biogas production (Figure 8). The simulated production changes however reduced the regional food production (the number of calories produced from food crops, dairy, and meat) as energy leys replaced spring barley. Even if some of the lost food production could be compensated by dietary shifts to less red meat and dairy products (Aleksandrowicz et al., 2016), the conflict with food production is one of the major limitations for increased production of agricultural bioenergy (Popp et al., 2014; Tilman et al., 2009; Vera et al., 2022).

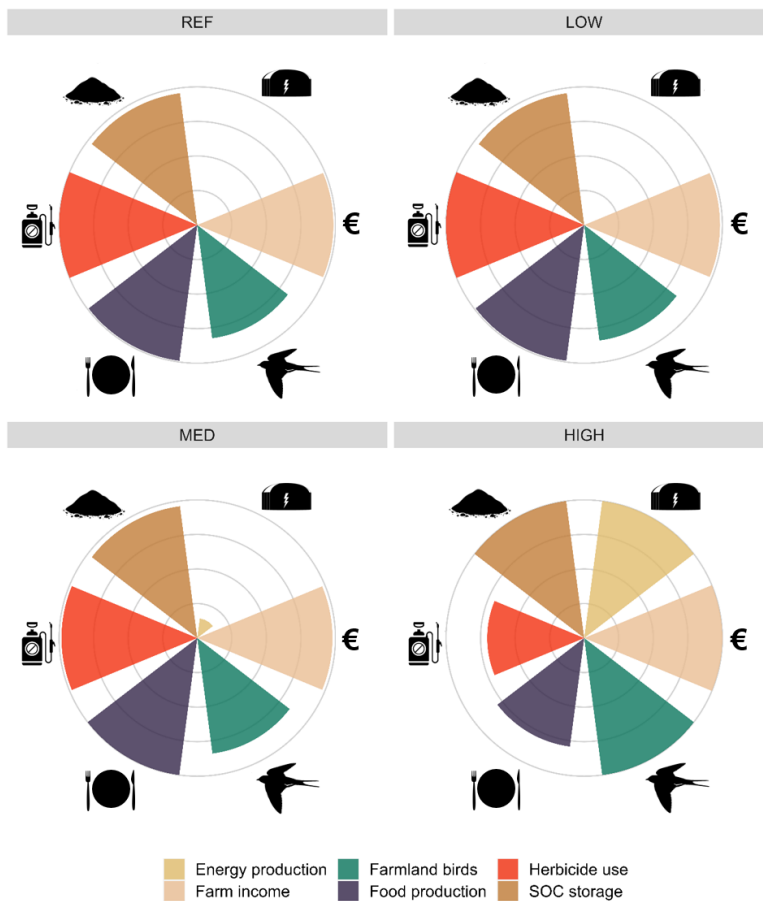


Figure 8. The predicted impact on energy production, farm income, farmland birds, food production, pesticide use, and soil organic carbon (SOC) storage in the reference scenario (REF) and the three energy ley scenarios (LOW, MEDIUM, HIGH). The impact for all variables has been normalised by dividing the impact value by the maximum variable value (scale 0-1). The figure is taken from Chapter IV, with variable icons sourced from BioRender.com.

The results of **Chapter IV** suggest that agricultural bioenergy could not only contribute to the decarbonisation of society by providing renewable energy but potentially also mitigate some of the environmental problems of intensive agriculture. Integrating grassland leys in crop rotations is a relatively easy and low-risk practice for farmers (Ford et al., 2024) that could benefit multiple agriculturally important ecosystem services in intense agriculture (Martin et al., 2020). In the studied region, grassland leys are already commonly used in crop rotations to produce ensiled fodder and hay for cattle and horses, indicating few practical barriers to the uptake of additional ley production. However, our results show that the increased uptake of energy ley reduced the production of fodder ley, resulting in a shift in livestock production towards fewer cattle and more granivores for the higher energy ley scenarios. While we found no major loss of utilised SNGs in our energy ley scenarios, a reduction in the number of grazing cattle generates risks for grassland abandonment with concurrent biodiversity loss (Elliott et al., 2023).

Given the high opportunity costs on productive arable land, our results show that the uptake of energy ley comes at a high cost. A hectare-based subsidy of 350 € ha⁻¹ for energy ley production is likely unrealistically high under current agricultural policies but was used in our study to simulate a high demand for biogas substrate. Sweden has set ambitious climate targets, including no net emissions of GHG by 2045 and a 70% emission reduction of domestic transportation by 2030 (Swedish Environmental Protection Agency, 2024), indicating that the need for fossil-free energy and fuel is becoming increasingly important. Whether agricultural bioenergy is included in the pathway towards a low-carbon society is uncertain and highly dependent on the trade-offs or synergies society and landowners are willing to accept.

Conclusion and final remarks

Climate change and biodiversity loss are two interconnected and complex global challenges. The urgency of finding and adopting mitigation and conservation strategies however carries the risk of generating new sustainability issues if these interlinkages are not addressed. Climate change and biodiversity loss hence have to be tackled together. In this thesis, I have focused on bioenergy production from the agricultural landscape – a source of renewable energy that has received increasing attention as a multifunctional climate mitigation strategy. By comparing different bioenergy strategies and their impact on biodiversity and ecosystem services, my thesis highlights the challenges of increasing agricultural bioenergy production without causing competition with the demand for food, feed, fibre, and resources from other sectors, including nature conservation.

I found that one of the most promising bioenergy strategies is the integrated production of bioenergy crops in intensive arable cropping regions. It could serve as a multifunctional climate mitigation strategy by positively affecting multiple ecosystem services and taxonomic groups (Chapter I). These benefits are nevertheless difficult to achieve without substantial financial incentives and consequences for food production (Chapter IV). Moreover, intensive biomass production is not beneficial for all taxonomic groups and species, and the increased bioenergy production may indirectly harm biodiversity by the loss of species-rich habitats when farm structure and agricultural production are altered (Chapter IV). Despite the environmental benefits offered by energy crops, such as increased carbon sequestration and reduced use of pesticides, multifunctional bioenergy systems cannot replace sustainable circular food systems that maintain food production or biodiversity conservation measures that preserve or recreate the habitats needed by the diverse group of species inhabiting the agricultural landscape.

An alternative bioenergy strategy is to produce bioenergy crops on marginal and abandoned land. In theory, this strategy offers an opportunity for sustainable biomass production without conflicting with other land uses, but as shown in Chapters II and III, neither of these land types offers a simple and unproblematic solution to the increasing demand for biobased energy. My thesis shows that the area of unused land in southern Sweden is small, and these sites may hold high biodiversity values. In addition, I found that marginal land generally has a smaller area and lower productivity than the surrounding arable land, indicating lower cost-

efficiency for intensive production. Using remote sensing, I showed that marginal land in most cases still has various use values, suggesting that the conflicts with food production, recreation, and biodiversity conservation are not resolved when marginal land or abandoned land is used for bioenergy production.

My thesis emphasises the importance of including both ecosystem services and biodiversity when evaluating bioenergy strategies to avoid conflicts between climate action and biodiversity conservation. This requires a more representative inclusion of multiple taxonomic groups in bioenergy studies, as well as a better understanding of which habitats benefit biodiversity so that policies can be designed that ensure that these ecosystems are preserved while mitigating climate change. However, the climate is already changing, and multifunctional bioenergy strategies may also offer opportunities for climate adaptation by increasing the productivity and climate resilience of arable land. Further research is needed to better understand the effect of climate change and climate adaptation on farming decisions and farmer attitudes to bioenergy crop cultivation in different landscape contexts. Finally, although sustainably produced bioenergy can be part of the path towards a fossil-free society, global climate goals cannot be reached without substantial reductions in energy use and consumption.

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